Potential landslide tsunamis near Aitape, Papua New Guinea

Philip Watts[1], Masafumi Matsuyama[2], and David R. Tappin[3]

[1]***Applied Fluids Engineering, Inc., Long Beach, California, U.S.A.***
[2]***Central Research Institute, Electric Power Industry, Abiko, Chiba, Japan***
[3]***British Geological Survey, Keyworth, Nottingham, United Kingdom***

Abstract. The 1998 Papua New Guinea (PNG) tsunami is now believed to have been generated by an underwater slump. Could future slumps threaten the same coastline? Two sites of potential tsunamigenic mass failure are identified from the Kairei bathymetry acquired off of the northern coast of Papua New Guinea. The geomorphology of these sites will be explained. Failure could be triggered at one or more of these sites following a nearby earthquake in this seismically active region. Moreover, severe faulting of the continental slope allows for water migration along control faults that may induce failure tens of minutes after a main shock. Regardless of the cause of failure, a Green's function approach is used to evaluate tsunami amplification along the shoreline. Almost the entire affected shoreline experiences strong tsunami focusing for one site or another. In addition, a sensitivity analysis shows that moving the location of failure by 10 km can shift peak run-up along the coastline by up to 5 km. A large uncertainty in the location of mass failure translates into a large uncertainty in the location of peak run-up. The implications for tsunami hazard assessment will be discussed.

1. Introduction

On 17 July 1998 a tsunami struck northern Papua New Guinea (PNG) about 20 min after a nearby magnitude 7 earthquake (Ripper and Letz, 1999). Shortly after 7 PM local time, more than 25 km of coastline home to at least 10,000 people was swept clean by water approximately 10 m high. More than 2200 people perished during the tsunami or shortly thereafter. The maximum measured water height of 15 m above sea level was much larger than expected and constitutes the largest documented tsunami related to a magnitude 7 earthquake in the 1990s (Kawata *et al.*, 1999; McSaveny *et al.*, 2000). The scale of the tragedy, the unexpectedly large tsunami amplitude, and the complex regional geology have motivated an international effort to understand tsunami generation (Davies, 1998a, 1998b). One of the goals of this effort is to assess future tsunami hazards for the devastated area (Tappin *et al.*, 1999).

Eyewitness accounts from the village of Malol describe the tsunami arriving just after a strong aftershock, or about 21 min after the main shock (Davies, 1998a). These carefully documented observations raise difficult challenges. A tsunami generated by coseismic displacement would arrive at least 10 min too early if the main shock has an epicenter on the Australian Plate. Tsunami generation beyond the New Guinea Trench would require an epicenter 180 km from the PNG shoreline to reproduce tsunami

[1]Applied Fluids Engineering, Inc., 5710 East 7th Street, PMB #237, Long Beach, CA 90803, U.S.A. (phil.watts@appliedfluids.com)

[2]Central Research Institute, Electric Power Industry, 1646 Abiko, Abiko-shi, Chiba-ken 270-1194, Japan (matsu@criepi.denken.or.jp)

[3]British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG, United Kingdom (d.tappin@bgs.ac.uk)

arrival times. This is well beyond published epicenter locations and outside of the apparent tsunami source region (Kikuchi *et al.*, 1999; Geist, 2000). These facts argue for mass failure tsunami generation and help explain the difficulties experienced when trying to simulate this event prior to the marine surveys (Titov and González, 1998; Geist, 1998).

The Kairei bathymetry revealed a large arcuate amphitheater near 2.89°S and 142.26°E that appears to have been formed by retrogressive failure (Tappin *et al.*, 1999). A fresh slump at the foot of the amphitheater was identified as the source of the tsunami (Tappin *et al.*, 2001). This particular mass failure is termed an underwater slump on account of deep rotational failure in stiff clay (Prior and Coleman, 1979; Edgers and Karlsrud, 1982; Schwab *et al.*, 1993; Hampton *et al.*, 1996). The narrow distribution of maximum run-up along the coastline indicated local tsunami generation directly off Sissano Lagoon, in the vicinity of the amphitheater (Kawata *et al.*, 1999). Simulations performed with the Kairei bathymetry have confirmed that wave refraction by two submarine canyons focused tsunami energy onto Sissano Lagoon (Matsuyama *et al.*, 1999; Piatanesi and Heinrich, 2001). However, there is also a significant amount of wave energy directed along the axis of slump failure that impacts the PNG coastline (Iwasaki, 1997; Watts *et al.*, this volume).

The locations of fresh headwalls, breccia blocks, scree slopes, tension cracks, basement faulting, fluid venting, chemosynthetic fauna, and authigenic carbonates define the tsunami source region (Moore *et al.*, 1986; Orange *et al.*, 1999). Tappin *et al.* (2001) use the relative age of seabed features and the size of young mussels to estimate the slump age. Synolakis *et al.* (2001) use seismic and T phase records to show that slump failure corresponds to the 09:02 GMT landslide earthquake. The 10-min delay in mass failure may be attributed to high pressure water advecting from the subduction zone up the control fault located underneath the slump (Sibson, 1981a, 1981b; Tappin *et al.*, 2001). The main shock appears to arise from shallow dipping rupture along the subducting Pacific Plate at an initial depth of around 10 km. Since far-field tsunami amplitudes depend primarily on moment magnitude, the shallow dipping fault reproduces the 20 cm tsunami measured near Japan (Satake and Tanioka, 1999; Tanioka, 1999). The underwater slump, in turn, generates a local tsunami that matches the observed time of arrival, peak amplitude, and run-up distribution (Tappin *et al.*, 2001; Synolakis *et al.*, 2001).

2. Objectives

Knowledge of offshore structures, previous mass failure scars, sediment types, sedimentation rates, subsidence rates, and other geological features enables prediction of mass failure during or following a nearby earthquake. Prediction of mass failure in turn enables tsunami hazard assessment of landslide tsunamis. We will invoke our interpretation of the tectonic paradigm off of Sissano Lagoon to posit future mass failure locations. We then propose to locate vulnerable sections of coastline along northern PNG near the affected region of the 1998 event. This process does not consider the tsunami amplitude explicitly and instead addresses solely the longshore amplitude distribution through the use of a linear Green's function. Given the current state of the art, we seek to evaluate this hazard assessment process and to consider its implications for tsunami hazard mitigation along the northern coast of PNG. A more detailed hazard assessment is left for future work.

3. Methodology

The significant threat of landslide tsunamis promotes further reliance on marine surveys in addition to traditional seismic tools. The primary tool of marine surveys is swath mapping of the sea floor bathymetry. We present an analysis of tsunamigenic sites off of northern PNG based solely on the morphology of the sea floor. Sites of potential underwater landslides are identified from the multibeam bathymetry acquired during the Kairei cruise SOS-1 (Tappin *et al.*, 1999, 2001). Specifically, we look for indications of thick sediment cover and signs of previous sediment slumping that form amphitheaters similar to the source of the 1998 tsunami. We consider a slump most likely to occur near a control fault or along a slope subject to tectonic oversteepening during subduction erosion (specifically of the Bismarck Sea Plate). Because we consider slumping within this specific tectonic paradigm, the tsunami sources used here apply exclusively to sediment starved margins comprised of stiff clay and subject to significant faulting. This sediment is not normally shaken loose by ground motion and probably has a low enough water content to preclude significant pore pressure increases (Tappin *et al.*, 2001; Synolakis *et al.*, 2001). Once these geological conditions are met, our results depend solely on the depth and size of slumping. The depth governs both the amplitude and the horizontal dimension of the tsunami source, whereas the size affects primarily the tsunami amplitude (Watts, 1998).

The Green's function is a linear concept, and so we adopt a linear tsunami propagation code for this work (Matsuyama *et al.*, 1999). The nonlinear stage of onshore inundation is omitted from our work because the simulation has a reflective wall at a water depth of 10 m. While tsunami hazards usually involve onshore inundation, we feel more limited by our geological knowledge, large simulation domain, and lack of nearshore bathymetry for the work undertaken here. To formulate a Green's function, we posit realistic tsunami sources generated by potential underwater slumps within suspected sediment deposits. Each tsunami source is an analytic function that has a wavelength of around 7 km (based on a common failure depth of 1200 m) and a maximum depression amplitude of 1 m (in keeping with traditional Green's functions). As in the 1998 event, the actual tsunami amplitude could be much greater, but depends on local sediment properties that remain unknown. Hence, we consider the tsunami amplification factor instead of the actual tsunami amplitude. We will assess vulnerability based in part on wave energy focusing, as occurred at Sissano Lagoon in 1998. These regions will invariably be the most devastated by the next tsunami attack.

We chose two tsunami sources based on extensive examination of the

Kairei bathymetry. A tsunami source corresponds to an initial free surface shape given to the numerical simulation at time $t = 0$. The simulation then propagates the wave according to linear shallow water wave theory. The tsunami sources are symmetric about an axis superposed along the expected trajectory of slump failure. The analytical form of the tsunami sources is precisely that given by Watts *et al.* (this volume). Source A is a slump that fails next to the 1998 PNG slump with a width of 4 km, an orientation 15 degrees west of due north, and a tsunami origin at 2.883°S 142.267°E. Source B has a failure width of 6 km, an orientation 20 degrees east of due north, and a tsunami origin at 2.900°S 142.433°E. We move the tsunami origin by 10 km along the points of the compass to yield different longshore amplitude distributions. We are concerned with the displacement of maximum amplification factors due to any uncertainty in the precise location of slumping.

4. Results

Figures 1–5 show the longshore amplitude distributions of source A with five distinct tsunami origins. Figures 6–10 document the respective results for source B. The first result that we notice is peak tsunami amplitudes 1–3 times greater than the characteristic tsunami amplitude at the source. The confluence of low lying or unsheltered coastline with maximum tsunami amplification reveals the severe vulnerability of the Sissano Lagoon coastline to tsunami attack. The hazard is compounded by the likelihood of further subsidence that would presumably accompany future earthquakes in the region (McSaveny *et al.*, 2000). While less exposed, other stretches of coastline are similarly imperiled. For example, source B reveals coastline near Malol and Aitape that are also subject to large amplification factors due to tsunami focusing by Yalingi canyon. This coastline is being uplifted by the Bismarck Sea Plate and therefore becomes further protected in geological time (Tappin *et al.*, 2001). There are also no villages at the sites of maximum amplification, as opposed to the former sites of Sissano and Arop villages.

Future submarine mass failure within the amphitheater may occur 10 km to the east, altering the location of the maximum amplification factor, but not significantly altering its value. The combined results for source A show that a subsequent landslide tsunami near the source of the 1998 event could strike anywhere along the sand spit in front of Sissano Lagoon. Specifically, our simulations show that moving the source location by 10 km can shift peak coastal amplitudes by up to 5 km. Therefore, uncertainty in future tsunami source location reveals that a much larger portion of coastline near Sissano Lagoon is actually vulnerable to large tsunami amplification. By superposing the five results from one of the tsunami sources, we find that any place along a 50 km section of shoreline can be affected by strong tsunami focusing, defined as having an amplitude greater than unity. We therefore find it difficult to restrict our assessment of vulnerability to specific village sites.

Despite the variations in peak amplification noted above, there is a reg-

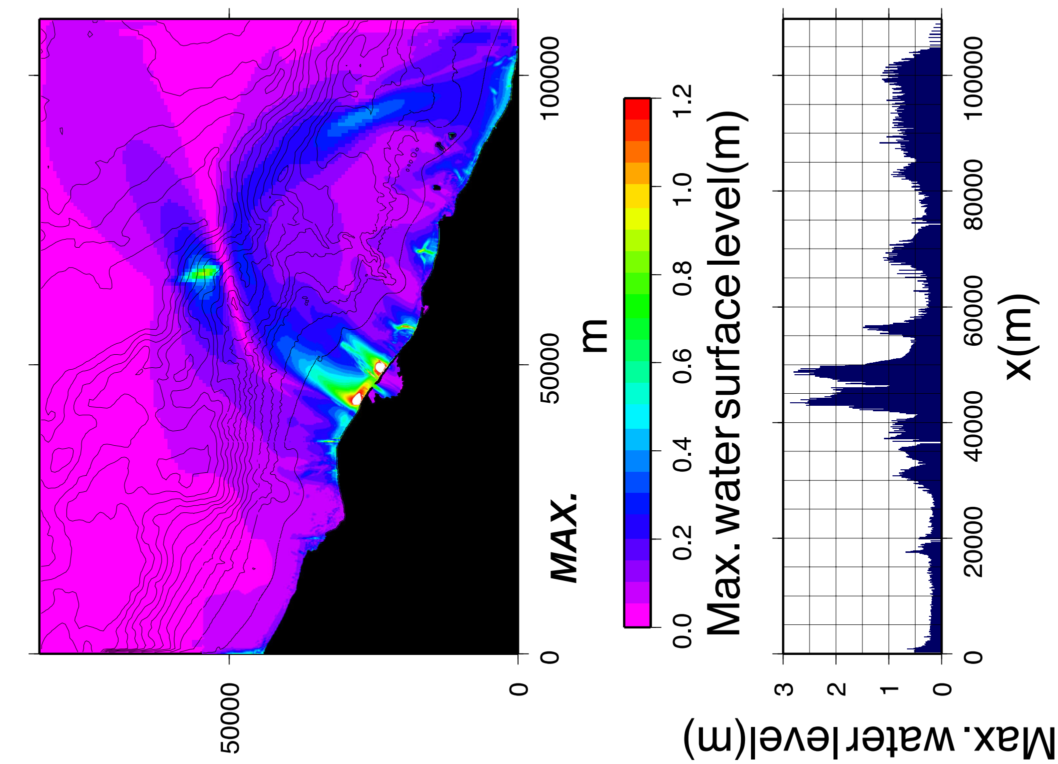

Figure 2: Results for source A displaced 10 km to the north.

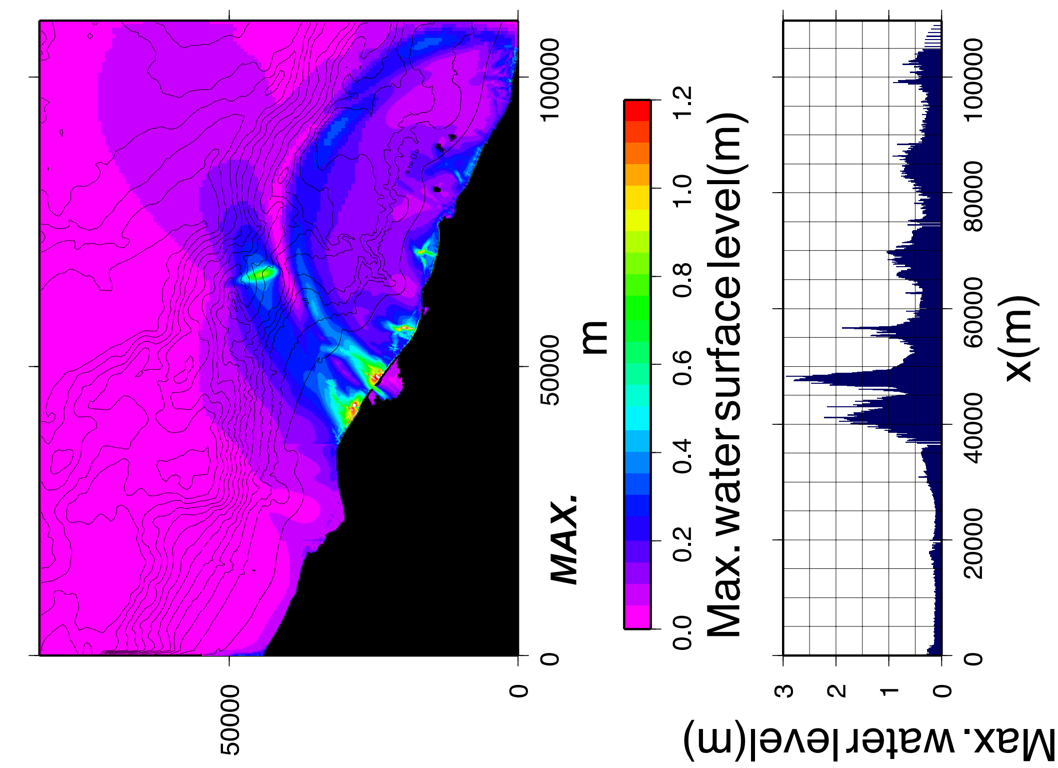

Figure 1: Source A longshore amplitude distribution.

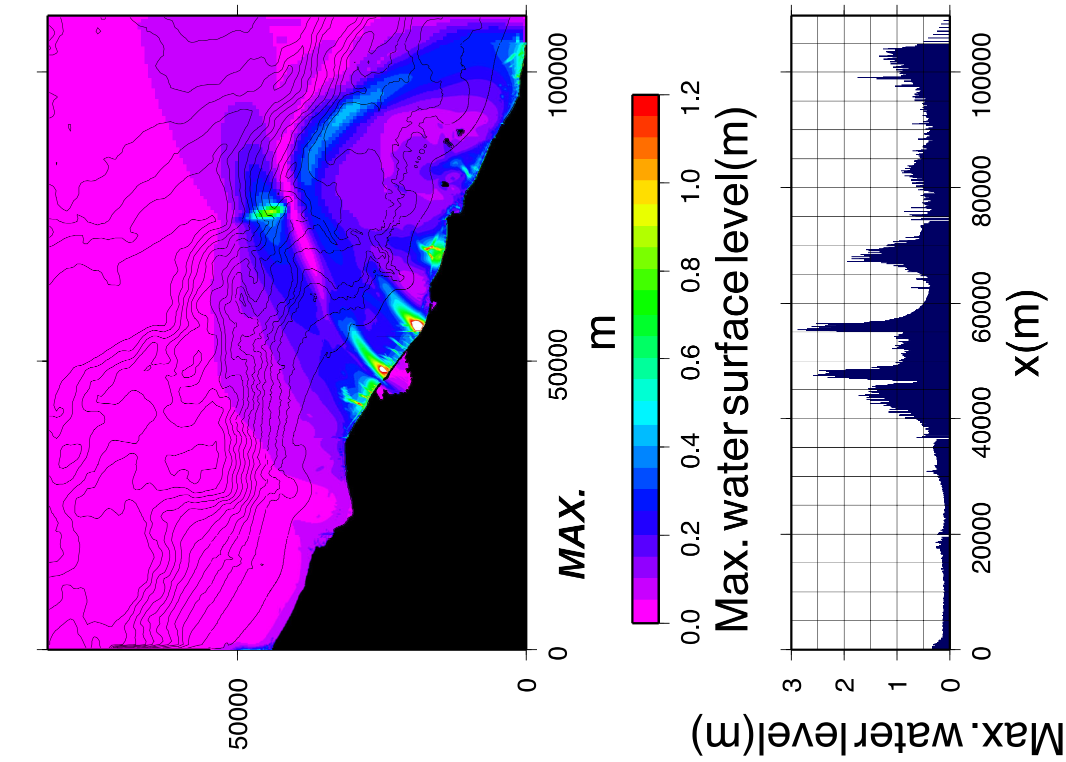

Figure 3: Results for source A displaced 10 km to the east.

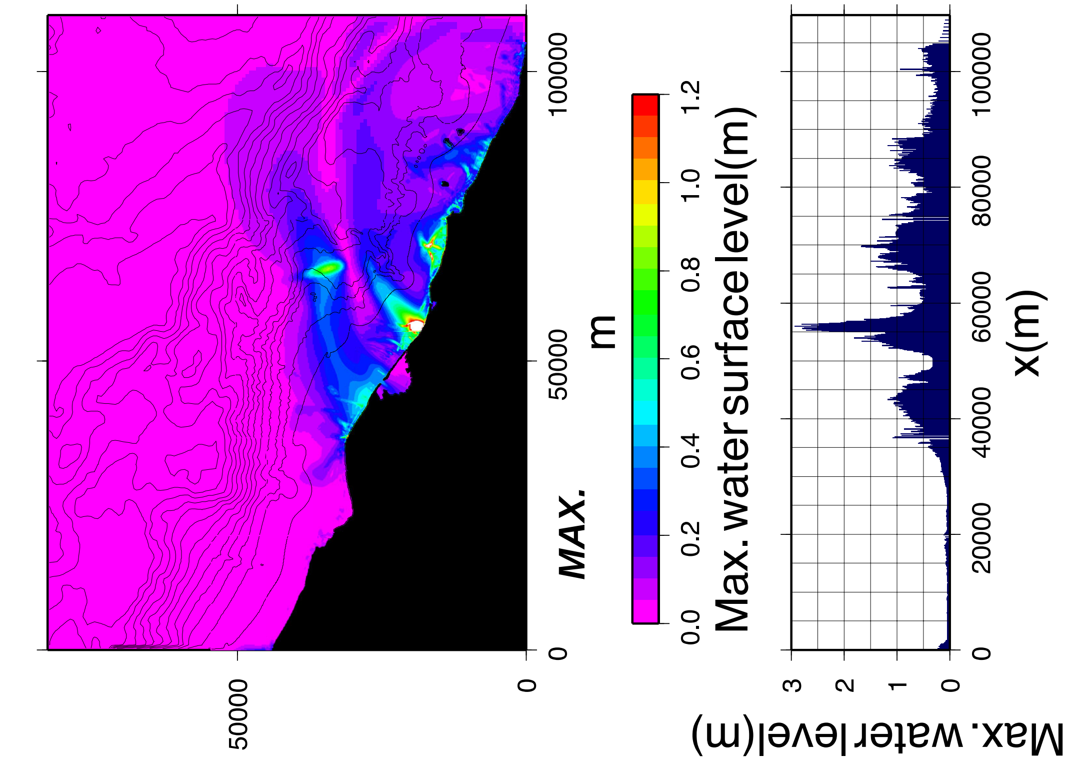

Figure 4: Results for source A displaced 10 km to the south.

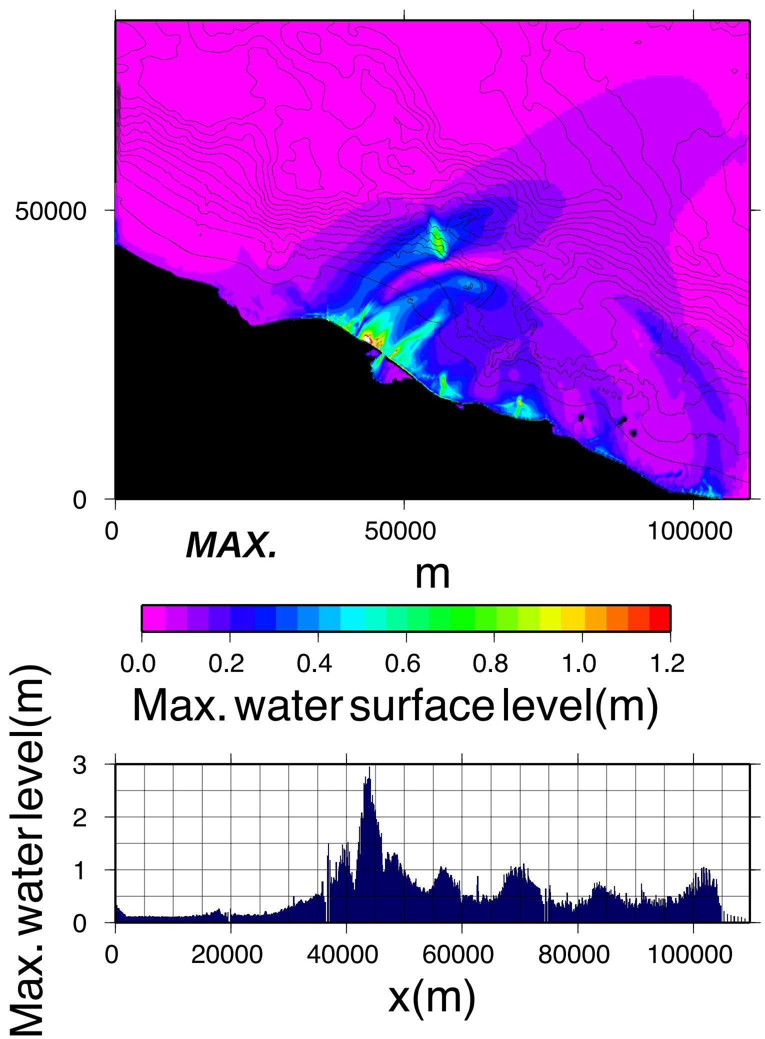

Figure 5: Results for source A displaced 10 km to the west.

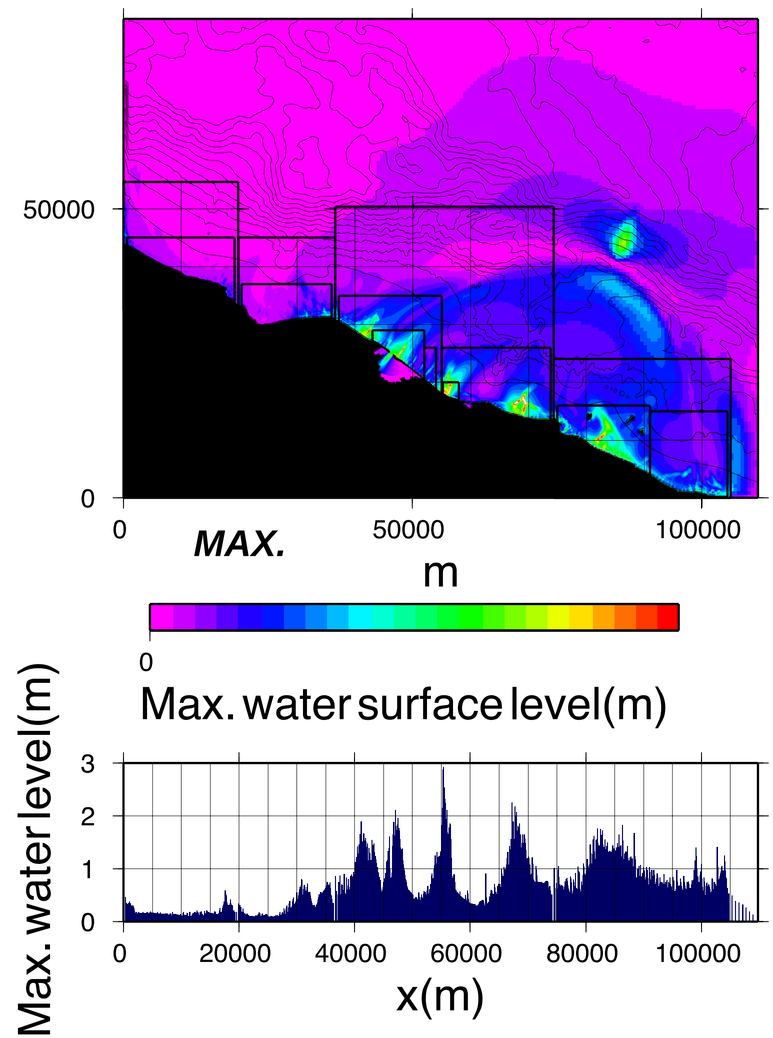

Figure 6: Source B longshore amplitude distribution.

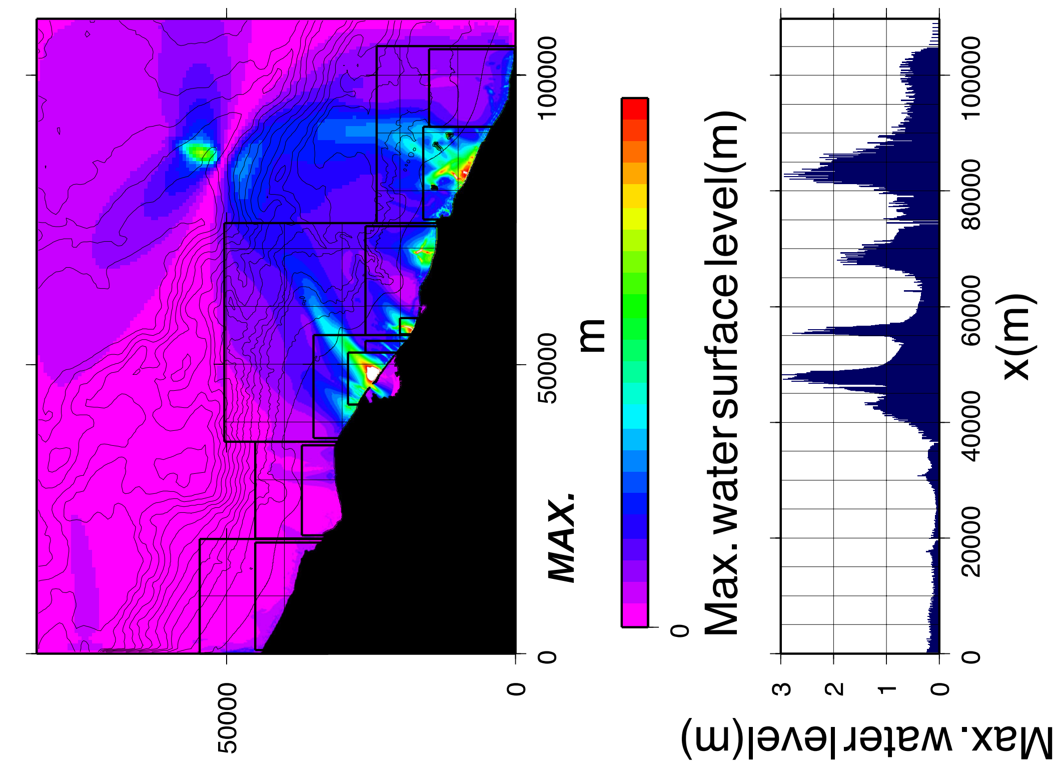

Figure 7: Results for source B displaced 10 km to the north.

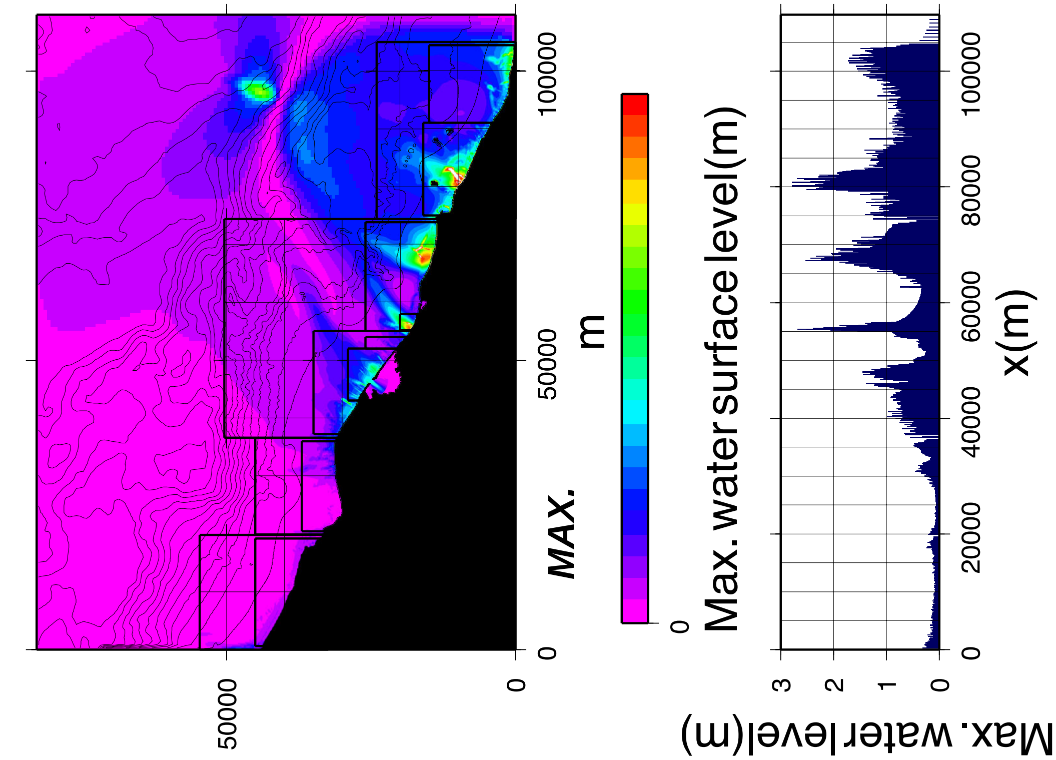

Figure 8: Results for source B displaced 10 km to the east.

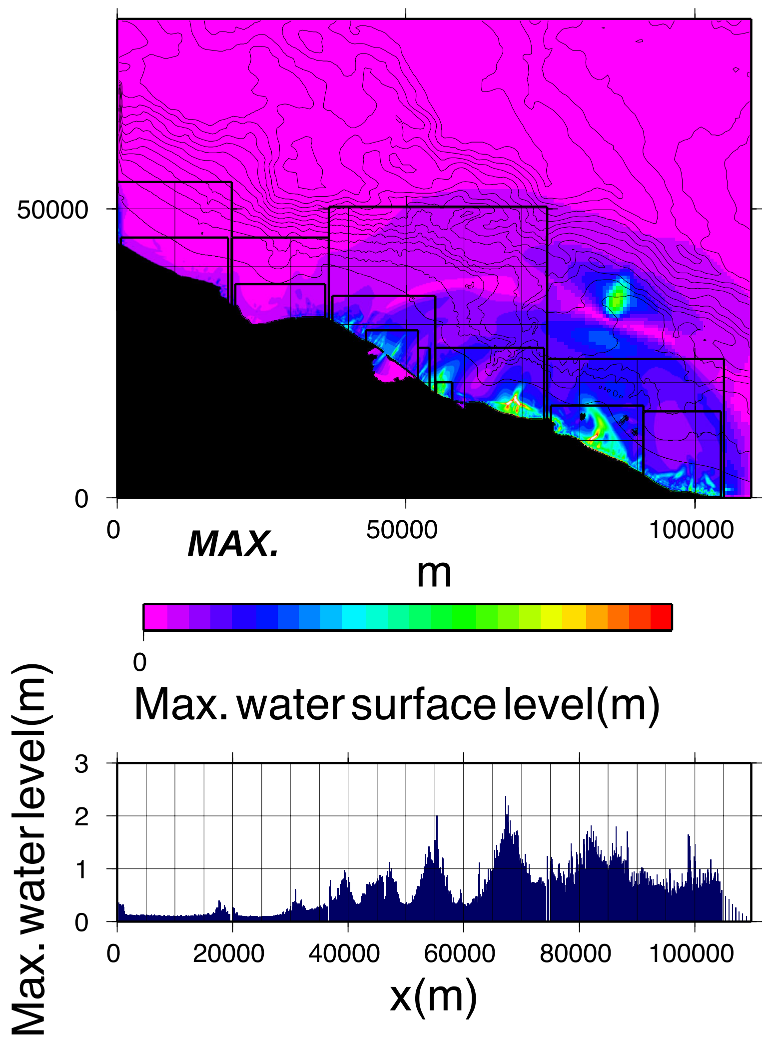

Figure 9: Results for source B displaced 10 km to the south.

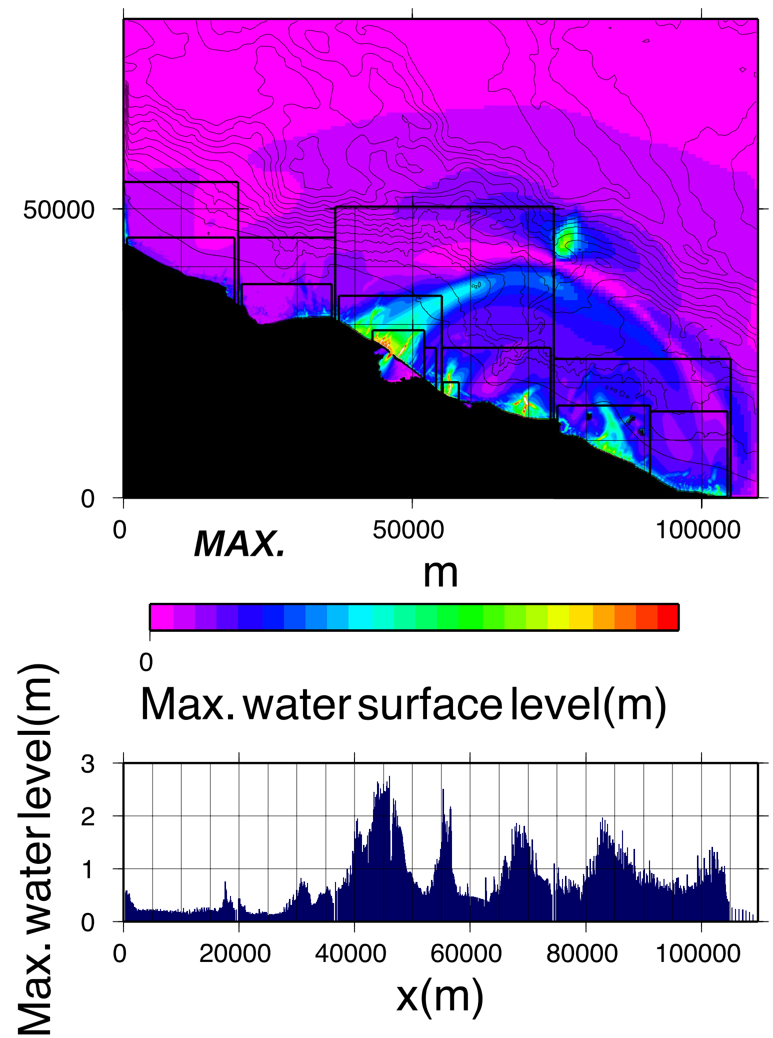

Figure 10: Results for source B displaced 10 km to the west.

ular pattern to the longshore amplitude distribution. For source A, strong amplification factors are consistently noted near the previous villages of Sissano and Arop, between Arop and Malol, and between Malol and Aitape. For source B, an additional amplification occurs east of Aitape. These observations indicate that the deep water associated with Yalingi canyon protects the village of Malol by refracting waves to the east and to the west. Likewise, Aitape is protected by a tectonic indentation in the continental shelf documented on the Kairei bathymetry. On the other hand, the former villages of Sissano and Arop consistently receive focused tsunami waves due to the extensive subsiding delta fronting Sissano Lagoon. Some stretches of coastline are consistently more vulnerable to tsunami attack than others.

5. Conclusions

The Green's function approach to landslide tsunami sources provides useful tsunami hazard assessment information. The cumulative effects of tsunami propagation are integrated to produce a longshore amplitude distribution. In the case of PNG, the amplitude distribution can be correlated with onshore villages to assess tsunami hazard. Our results indicate that local landslide tsunamis produce mean run-up that is comparable to the characteristic tsunami amplitude as defined by Watts (1998, 2000). We show that tsunami focusing can amplify the source threefold. We find consistent locations for the strongest tsunami amplification that depend on offshore bathymetry and are largely independent of source location. However, almost the entire affected shoreline can experience tsunami amplification depending on the precise tsunami source location. We conclude that geographical uncertainty in the location of mass failure translates into a similar uncertainty in the location of peak run-up. This combination of certainty and uncertainty shifts the burden of tsunami hazard assessment from tsunami source and propagation characteristics back to the nearshore and onshore characteristics of tsunami attack. For example, the subsiding region between Aitape and Serai that includes Sissano Lagoon is clearly vulnerable to future tsunami attack (Tappin *et al.*, 2001). There is no high ground on which to seek shelter from uniformly strong tsunami amplification.

In sum, we find that the "design wave" approach, where tsunami interaction with the coastline is simulated for a hypothetical wavelength and amplitude, may yield more tsunami hazard information than our sensitivity analysis of source location. In the "design wave" approach, an inverse problem is posed that seeks those tsunami characteristics that can inflict damage or casualties at certain locations. Local bathymetric and topographic features that provide relief from tsunami attack therefore raise the hazard threshold and decrease the probability of damage or casualties. The "design wave" approach seeks to identify the hazard threshold as well as the probability of reaching that threshold. Once a hazard threshold is established at each location of interest, one may then seek potential tsunami sources that can reach the threshold, regardless of the precise Green's function results.

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6. References

Davies, H.L. (1998a): *The Sissano tsunami 1998*. University of Papua New Guinea Press, Port Moresby, Papua New Guinea.

Davies, H.L. (1998b): Geology of the Aitape coast: Transpressional faulting and uplift in the forearc of the New Guinea Trench. *Eos Trans. AGU, 79,* 563.

Edgers, L., and K. Karlsrud (1982): Soil flows generated by submarine slides: case studies and consequences. *Nor. Geotech. Inst. Bull., 143,* 1–11.

Geist, E.L. (1998): Source characteristics of the July 17, 1998 Papua New Guinea tsunami. *Eos Trans. AGU, 79,* 571.

Geist, E.L. (2000): Origin of the 17 July, 1998 Papua New Guinea tsunami: Earthquake or landslide? *Seismol. Res. Lett., 71,* 344-351.

Hampton, M.A., H.J. Lee, and J. Locat (1996): Submarine landslides. *Rev. Geophys., 34*(1), 33–59.

Iwasaki, S. (1997): The wave forms and directivity of a tsunami generated by an earthquake and a landslide. *Sci. Tsunami Hazards, 15,* 23–40.

Kawata, Y., and International Tsunami Survey Team members (1999): Tsunami in Papua New Guinea was intense as first thought. *Eos Trans. AGU, 80*(9), 101.

Kikuchi, M., Y. Yamanaka, K. Abe, and Y. Morita (1999): Source rupture process of the Papua New Guinea earthquake of July 17th, 1998 inferred from teleseismic body waves. *Earth Planets Space, 51,* 1319–1324.

Matsuyama, M., J.-P. Walsh, and H. Yeh (1999): The effect of bathymetry on tsunami characteristics at Sissano Lagoon, Papua New Guinea. *Geophys. Res. Lett., 26,* 3513–3516.

McSaveny, M.J., J.R. Goff, D.J. Darby, P. Goldsmith, A. Barnett, S. Elliot, and M. Nongkas (2000): The 17 July, 1998 tsunami, Papua New Guinea: Evidence and initial interpretation. *Mar. Geol., 170,* 81–92.

Moore, J.C., B. Carson, B.T. Lewis, S.D. Ritger, D.C. Kadko, T.M. Thornburg, R.W. Embley, W.D. Rugh, G.J. Massoth, M.R. Langseth, G.R. Cochrane, and R. Scamman (1986): Oregon subduction zone: Venting, fauna and carbonates. *Science, 231,* 561–566.

Orange, D.L., G.H. Greene, D. Reed, J.B. Martin, W.B.F. Ryan, N. Maher, D. Stakes, and J. Barry (1999): Widespread fluid expulsion on a translational continental margin: Mud volcanoes, fault zones, headless canyons, and organic-rich substrate in Monterey Bay, California. *Bull. Geol. Soc. Am., 111,* 992–1009.

Piatanesi, A., and P. Heinrich (2001): Source characteristics of the July 17, 1998, Papua New Guinea tsunami inferred from run-up data. *J. Geophys. Res. B.*, submitted.

Prior, D.B., and J.M. Coleman (1979): Submarine landslides: Geometry and nomenclature. *Z. Geomorph. N. F., 23*(4), 415–426.

Ripper, I.D., and H. Letz (1999): The Sissano Lagoon (Aitape) tsunami: Which earthquake was responsible? Papua New Guinea Geological Survey Report, 99/7.

Satake, K., and Y. Tanioka (1999): The July 1998 Papua New Guinea earthquake and tsunami: A generation model consistent with various observations. *Eos Trans. AGU, 80,* 750.

Schwab, W.C., H.J. Lee, and D.C. Twichell (1993): Submarine landslides: Selected studies in the U.S. exclusive economic zone. U.S. Geol. Surv. Bull. 2002, U.S. Dept. of Interior, Washington, D.C.

Sibson, R.H. (1981a): Fluid flow accompanying faulting: Field evidence and models. In *Earthquake prediction: An international review,* edited by D.W. Simpson and P.G. Richards, American Geophysical Union Maurice Ewing Series, 4, 593–603.

Sibson, R.H. (1981b): Controls on low stress hydro-fracture dilatancy in thrust wrench and normal fault terranes. *Nature*, *289*, 665–667.

Synolakis, C.E., J.-P. Bardet, J.C. Borrero, H. Davies, S.T. Grilli, E.A. Okal, E.A. Silver, S. Sweet, D.R. Tappin, and P. Watts (2001): Slump origin of the 1998 Papua New Guinea tsunami. *Proc. R. Soc. Lond.*, accepted.

Tanioka, Y. (1999): Analysis of the far-field tsunami generated by the 1998 PNG earthquake. *Geophys. Res. Lett.*, *22*, 3393–3396.

Tappin, D.R., T. Matsumoto, and shipboard scientists (1999): Offshore surveys identify sediment slump as likely cause of devastating Papua New Guinea tsunami 1998. *Eos Trans. AGU*, *80*(30), 329.

Tappin, D.R., P. Watts, G.M. McMurtry, Y. Lafoy, and T. Matsumoto (2001): The Sissano, Papua New Guinea tsunami of July 1998—Offshore evidence on the source mechanism. *Mar. Geol.*, in press.

Titov, V., and F. González (1998): Numerical study of the source of the July 1998 Papua New Guinea earthquake. *Eos Trans. AGU*, *79*, 564.

Watts, P. (1998): Wavemaker curves for tsunamis generated by underwater landslides. *J. Waterway Port Coast. Ocean Eng., ASCE, 124*(3), 127–137.

Watts, P. (2000): Tsunami features of solid block underwater landslides. *J. Waterway Port Coast. Ocean Eng., ASCE, 126*(3), 144–152.